

FINDING THROUGH NDE THE THERMAL HISTORY AND METALLURGICAL  
STATUS OF A HEAT TREATABLE ALUMINUM ALLOY

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SUMMARY

In heat-treatable aluminum alloys it has long been accepted that decreased values of strength were accompanied by increases in electrical conductivity (C). In quality or processing control and trouble-shooting situations this has been useful for finding anomalies in or among aluminum alloy mail products. But the regression was always found as a wide scatterband where conductivity could not give a narrow range of possible strengths.

It was discovered for several alloys and quantified for 2219, that the scatterband formed by data from several lots and sources actually could be divided into groups with different histories. When specimens produced by created combinations of quenching-time and aging-time had their Hardness (H) vs Conductivity plotted on a H vs C format a fan-like dispersion of coordinated points was seen. Drawing locuses thru like times divided this fan into age-time and quench-time grids. Any particular C-H coordinate in this envelope then was seen as identifying the thermal history of the piece with that of C-H value. It was also found that progress in one direction on this format marked out the increase in the 2219 hardening precipitates  $\theta''$  and  $\theta'$ . Progress in the other direction marked out the increase in the softening precipitate  $\theta$ . So that even the particular metallurgical status could be found from the C-H coordinate of the specimen.

This work taught that the large C-H variations seen in accumulations of data most often represented variations in the material itself, not in measurement systems. The work also taught that variation in production material was tracible mainly to variation in

quench times. Should such variations be reduced the standard deviation of strength would be reduced and higher design strengths could be assigned to the alloy. In practical situations increases in design strengths (which conversely means reductions in assembly weight) are seen at 12%. The NDE measurements can serve this end by identifying and certifying grades of material before pieces are put into service. This strategy involves avoiding that apparently sound material which will fail early in its service life.

## DISCUSSION

The area of the technology that deals with nondestructively identifying aluminum alloy heat treatment anomalies or estimating the strength of alloy pieces has produced regressions that show softness associated with higher electrical conductivity. Unfortunately these regressions for all the available experiences with a given alloy are useful but so wide that no practical strength predictions have been possible from conductivity values. Except for those sophisticated projects which work toward creating standards the conductivity measurement are made with eddy current equipment which used a simple single handle probe to induce current in the object and scale the relative energy loss; relating this to conductivity in terms relative to the conductivity of the International Annealed Copper Standard (IACS).

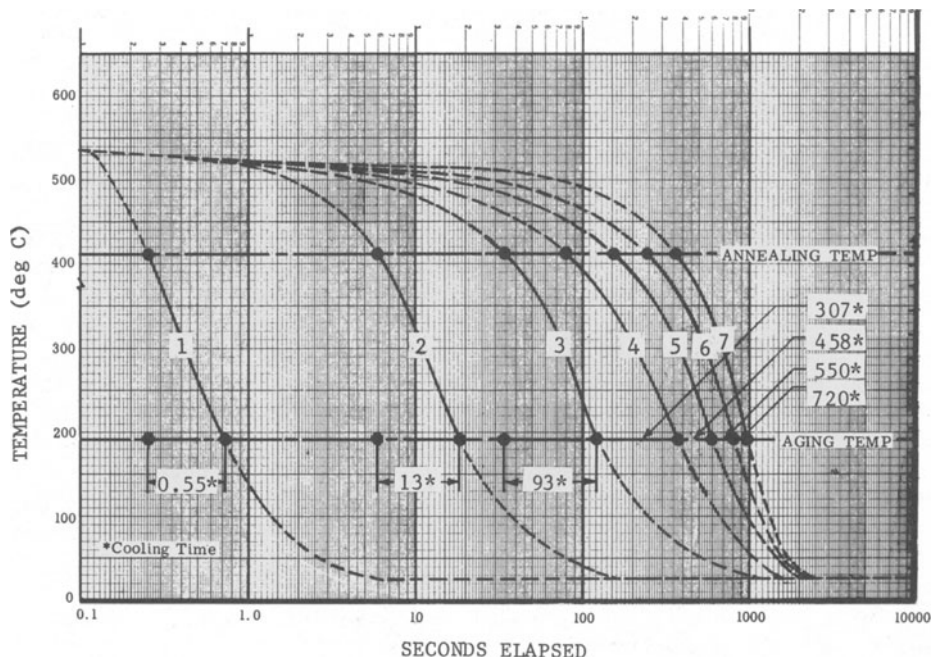


Figure 1

The investigation here to be described conducted graduated permutations of quenching time and aging time on the 2219 alloy. There were seven different quench rates which gave, at the end of each cooling, seven panels in the W condition (as quenched). They were identified as numbers 1 thru 7. The quench value recorded was the time it took to pass from 410 thru 190°C. These panels were allowed to age at room temperature for 96 hours to put the seven into the T42 condition before the start of the artificial aging scheduled at 190°C. Figure 1 shows the recorded and interpolated path of each of the panels on a Temperature vs log-time format. These paths were designed to replicate increasingly slower, or poorer quenches.

The effect on the Conductivity and Hardness (which proportionally represents strength) of these longer quenches can be seen in Figure 2. The familiar loss of Hardness (1 thru 7) is accompanied by a measured increase in Conductivity. The locus of this progress lies along A on 1, 2, 3, 4, 5, 6, 7. This path does cast itself along the accepted sense of aluminum's C-H regression (i.e., strength with low C to softness with high C). If we take the normal or well-quenched panel #1 and conduct it progressively through stages of aging time (A thru J) we find an extraordinary behavior. While hardness doubles, the conductivity changes hardly at all, that is up to the point E (Figure 2) which is met in 135 minutes. Then this C-H locus suddenly follows a quite different course. For 4000 minutes hardness drops, but only gradually, while C rises quickly relative to hardness. These changes are decelerating: it takes 2000 minutes to change the alloy from I the J as shown in Figure 2.

The same aging experience applied to a poorer quench (#3) gives a locus which has a similar shape though displaced down along the primary regression. The similar courses of the other panels (#4, 5, 6, 7) can now be appreciated. At the end of the fullest practiced age (I, 2000 minutes) the seven panels have C-H coordinates marking a track which parallels roughly the slope of the primary regression but hangs on the other border of all the C-H possibilities.

It is clear now that any of the C-H combinations within this sail-shaped envelope are possible and each for quite rational and explicit thermal-history and metallurgical reasons. This project was started with the intention of finding a sense of how much of the experienced variation of C with H might be attributed to metrology (measurement) errors and how much to metallurgical differences. The results before us show that in this span of abnormal preparations, material variations can easily explain a 10 point IACS spread of conductivity and a 25 spread Rockwell B Hardness points; and this is for pieces represented as either T6, or T85, or T87. The Bureau of Standards (Reference 1) work on 2219 referred to the metrology factor when it found that measurement differences between different companies, sites, and equipment on the same

materials spread the C-H relationship by nominally 0.4 point IACS. That investigation combined with this study and several in-progress works indicates that the wide historical C vs H variation recorded from all sources should be attributed to material differences.

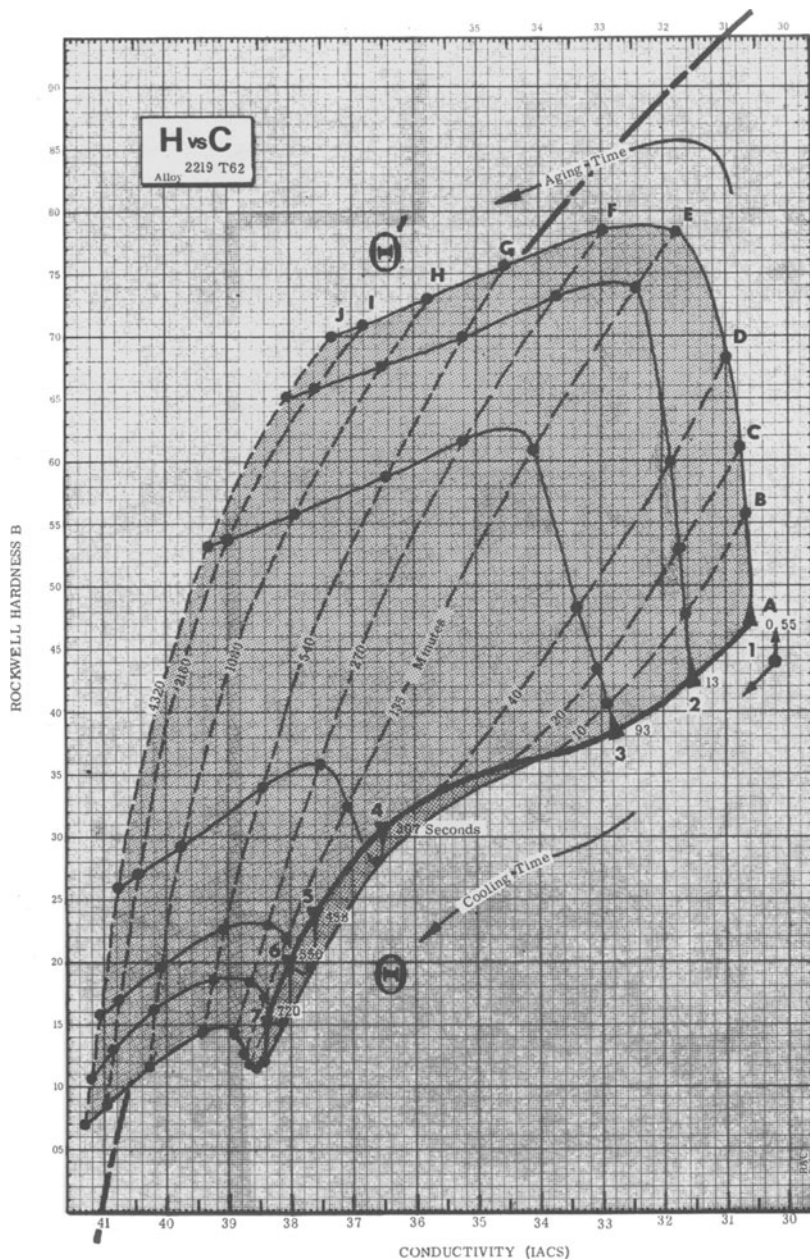


Figure 2

Were it not for compositional and residual strain differences it would be possible, in principle, to take the C-H coordinate for a specimen and report the exact quenching time and aging time which brought it to the measured state. Note how the C-H coordinates of C = 34 and HRB = 61 indicate 93 seconds to quench and 135 minutes of age. This ability is accurate enough to be outstandingly useful.

In general, engineers have been so taken up with mechanical properties as the gage of an alloy's state they use those numbers as proof of production accomplishment. The fallacy in this policy can be seen if we call all plate shipments with RB hardness of 70 or strength of 59 ksi "meeting specifications". Clearly if this received-stock has, at the same time, conductivities ranging from 37 to 33, as they might with the aging practices currently permitted, we do not have a single condition in the inventory. This leads us to the metallurgical discussion.

At temperatures greater than 300°C (the ones experienced during slow quench) we expect the coarse precipitates of  $\theta$  to form causing hardness-loss, essentially by taking the copper out of the matrix into these precipitates. It seems clear that this is what is happening in the longer quench time for panels 2, 3, 4, 5, 6, and 7 on the A locus. Panel #3 then, has more  $\theta$  than #2 and #1. The matrix material in the #3 panel has then a reduced ability to produce the  $\theta''$  and  $\theta'$ , the fine hardening precipitates formed below 200°C. But that matrix hardens by the same schedule as the rich matrix of panel #1. So, to be brief, the 1 to 7 locus at A represents a line of increasing  $\theta$ . But it takes one track with 1 thru 7 at A and a different one at 1 thru 7 at J.

Our analysis and expectation suggests that #1 panel's movement thru B, C, D, E with 190°C marks the precipitation and growth of  $\theta''$  and  $\theta'$  which hardens the piece greatly but, in the net, changes conductivity little. The severe inflection at E matches roughly the areas at which Rosen (Reference 2) in his sonic attenuation and velocity studies finds a shift from the coherence to the incoherency relationship between precipitates and matrix. Relief of matrix strain can account for the beginning of and subsequent development of higher conductivity. Note, the loss of strength with this phenomenon (E to J) is slow. But a different state must exist at I compared to E (on line 1) where C has changed 4.5 points IACS. The former conspicuously carries a finely dispersed net of high micro-residual strains to which poor corrosion resistance and some mechanical property differences are related. So we see here between E and J an axis which marks matrix relaxation and  $\theta'$  coarsening. This axis is nearly cross-wise to the major regression. So across-the-plot represents increasing maturity of the  $\theta'$  development while movement diagonally and down-the-plot, marks increasing amounts of  $\theta$  to the loss of the  $\theta'$  potential in the matrix fields. We have then a means for discovering the amount of the detrimental components

in pieces we wish to study either in the industrial quality control environment or in the metallurgical research laboratory.

Perhaps such a scale may be defined by formats laid onto Figure 2 where the start point (A1) is defined as no  $\theta$ , and the most- $\theta$ -possible is defined as the TB = 0, IACS = 41.5 position and the connecting line is divided into 100 equal parts. The important part of employing this analytical tool is to know beforehand whether the plan is on the no-age (the as-quenched) A line, or it is on the greatest-age I line from point I1 to TB = 0 and IACS = 41.5; or on lines in between.

The insight provided by combinations of C-H now permits a successful investigation into the kind and distribution of precipitating particles in a piece under study. Combinations is the new word. It has been heard often, because of the historical scatter seen in the C vs H relationship, that C is a poor indicator of the state of an aluminum alloy. A certain conductivity will allow a strength anywhere in a vertical span of this envelope. But also valid is the unusual criticism that the strength is just as incomplete an indicator of status of a piece. It is the C-H combinations which stipulates a singular status (within a circle of probable error).

It might have become apparent that these C-H positions can be used to draw nucleation diagrams. We believe so and are working on this. Normally, an alloy piece is quenched into a salt bath and held for a time. Different times increase the degree of precipitation occurring at that temperature. The start of the nucleation of a certain precipitate is then marked on a Temperature vs log-time format. The nucleation field boundary is usually seen as a large parabolic nose. The kind and distribution of precipitation is revealed through transmission electron microscopy, which unfortunately can hardly reveal a value for density or particle spacing. These easily measured C and H dimensions may be used skillfully for the expansion of metallurgical knowledge.

There is more to be gained from expanding testing than to just better define Horbogen's nucleation diagrams (Reference 3). His kind of diagram is prepared by observing change during an isothermal hold. In real life at a metal producers, alloy pieces penetrate nucleation conditions from the top descending thru the Temperature vs log-time format. We suspect that the nucleation boundaries produced from these entries will be shifted from the Hornbogen reference and these will represent more truly the events occurring in actual production metallurgical processes.

## CONCLUSIONS

For the 2219 alloy, the work-to-date carries the patterned

Conductivity vs Hardness data that reveals how unknown pieces were quenched and how much aging they have received. Clearly when we choose to limit excesses on these particular processing parameters we can exercise a real quality control on the metal for aerospace application. But there is more in this than a concrete ability to truncate the range of material errors, which is all that inspection does. Having surveyed the results of past production practices and inspection systems and placed these against late practices and these new insights we are seeing that by improving consistency we are within reach of using design values for familiar alloys that are 4 to 10% higher than those established 20 years ago.

Applied to the design of vehicles or payloads this can mean a reduction in the weight of heat treatable aluminum parts of 4 to 10% with corollary fuel savings or range increases. Gains in service functions are quite easy for the manufacturer or the user to calculate.

#### REFERENCES

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